An Empirical Study of Nonlinear Adjustment in the UIP Model using a Smooth Transition Regression Model

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Abstract

This study considers the nonlinear relationship between the expected exchange rate change and the interest rate differential, using STR models (ESTR and LSTR), with Sharpe ratios, interest rate differentials and exchange rate volatilities as the transition variables. The results generally conclude that UIP holds with the larger Sharpe ratio and higher exchange rate volatility regime, which is consistent with the transaction costs and limits to speculation hypotheses. However, the interest rate differential, which is generally not used much as a transition variable, but when used in this study the result fails to support UIP in the upper regime, which suggests it is the risk not the pure return that determines the transition.

Keywords: Uncovered Interest Parity; Smooth Transition Model (STR); Sharpe ratio; Limits to speculation; Carry Trade

JEL Classifications: F30; F31

1. Introduction

Uncovered interest rate parity (UIP) is one of the key theoretical relationships used in analytical work in both international finance and macroeconomics and is an important assumption in exchange rate models. It implies that the interest rate differential should be equal to the expected exchange rate change. However, UIP has been rejected in most empirical studies, as high interest rate currencies tend to appreciate rather than depreciate. It is possible that arbitragers could receive a higher return through selling foreign currency and investing in domestic currency if the interest rate differential is greater than the expected depreciation of the domestic currency against the foreign currency. In this scenario, speculation through a carry trade strategy could earn a double profit from both the interest rate differential and exchange rate movements. There isn't currently a consensus on how to explain the failure of UIP, although the potential explanations for UIP deviations include the failure of rational expectations, the existence of a time-varying risk premium and nonlinear adjustment.

Most empirical studies on UIP have generally relied on a linear framework. However, it is difficult for a linear model to capture any potential nonlinear adjustment. Recently nonlinear models have become more popular in empirically based macroeconomic studies, including studies on the business cycle, the term structure of interest rates and exchange rate models. This is partially due to increasing interest in forecasting parameters using nonlinear techniques (Clements et al., 2004). Studies suggest that the relationship between exchange rate movements and interest rate differentials may be nonlinear for a variety of reasons, including central bank interventions (McCallum, 1994; Anker, 1999; Cavoli and Rajan, 2006; Mark and Moh, 2007), transaction costs (Baldwin, 1990; Dumas, 1992; Michael et al., 1997; Chen and Wu, 2000; Samimi et al., 2009), heterogeneous traders (Brock and Hommes, 1996; Guillaume et al., 1997; Kilian and Taylor, 2003; Grauwe and Grimaldi, 2005) and the presence of limits to speculation (Lyons, 2001; Sarno et al., 2006; Baillie and Kilic, 2006; Amri, 2008; Baillie and Chang, 2011).

The smooth transition regression (STR) model has been applied widely in exchange rate determination studies, such as purchasing power parity (PPP), portfolio balance models and the monetary models. This is because in theory the behaviour of monetary policymakers in resisting rapid changes in the exchange rate and the interest rate could have a smoothing effect on UIP (McCallum, 1994). Some studies have compared the STAR model with other nonlinear models such as TAR (Balke and Fomby, 1997) and Hamilton's Markov regime-switching model (Hamilton, 1989), and indicate that the STAR model provides a more realistic representation of exchange rate movements, because it is smoother and more gradual. Motivated by the previous literature, this paper will examine the nonlinear relationship between the expected exchange rate change and the interest rate differential using the STR models.

The main contributions in this paper with respect to previous studies are the following. First of all, a variety of previous studies focus on the relationship between the exchange rate change and the forward premium. But, in this paper, the interest rate differential is used rather than the forward premium, as the latter required the additional assumption of CIP holding. In addition the forward market for emerging countries developed much later than the developed countries, so there is a lack of data when using the forward rates (Frankel and Poonawala, 2010). Also the interest rate differential is considered as an important instrument for the conduct of monetary policy and in the carry trade, so it is the interest rate differential which is the main focus in this study. Secondly, we use a linearity test to decide on the presence of nonlinearity and to select the most appropriate STR models (LSTR or ESTR), rather than decide on the form of nonlinear model in advance (Baillie and Chang, 2011). Thirdly, different transition variables such as the Sharpe ratio, interest rate differential and exchange rate volatility are included in this study. The use of exchange rate volatilities as transition variables provides a link between the risk premium (see Tai, 2004) and non-linearity as an explanation for UIP failure.

The data used in this study follows other similar studies and consists of monthly data of the one month interest rate and bilateral exchange rates against the US dollar. The reasons we chose the currencies used in this study is because the developed countries have the most traded currencies, whilst the sample of emerging currencies have not been used extensively in this type of study before and also have had varying experiences of their own financial crises. The data begins in 1986 for the developed countries, but in the early 1990s for the emerging economies.

The main findings of this study are that there is evidence of non-linear adjustment of the exchange rate in the context of UIP and that measures of risk such as the Sharpe ratio are the best transition variables, which provides further evidence of the importance of non-linearity to exchange rates, as shown in other studies such as Michael *et al.* (1997), as well as the need to incorporate risk into exchange rate models as also found by Tai (2004).

The remainder of this paper is organized as follows. Section 2 presents the previous literature outlining the nonlinear behavior of UIP based on the central bank intervention, transaction costs and the limits to speculation theories. In Section 3, the methodology is described, especially the STR models (LSTR and ESTR). Section 4 presents the main empirical analysis to determine whether nonlinear behavior affects UIP. Section 5 concludes and offers suggestions for further study.

2. Literature Review

2.1. Central Bank Intervention

One of the main causes of nonlinear adjustment of the exchange rate is central bank intervention in the foreign exchange markets. Generally monetary authorities tend to resist rapid changes in exchange rates and interest rate differentials. Even if central banks are not intervening to defend the exchange rate, they often tend to hold short-term interest rates relatively constant. This implies that short-term interest rate differentials will vary much less than other variables, which influences the risk of the country and might be a potential explanation for the negative parameter estimates of β.

The central bank intervention could have a smoothing effect on the relationship between interest rates and exchange rates, which may lead to smooth transition in the parameters of the UIP model. McCallum (1994) suggests that the behaviour of monetary policy could be responsible for the empirical failure of UIP. Anker (1999) investigates whether monetary policy can explain the UIP puzzle. The result is that a trade-off exists between the interest rate and exchange rate stability which could explain the failure of UIP and the policy reactions can explain why deviation from UIP differs systematically in terms of the exchange rate regime. The findings suggest that interest rate smoothing could be an explanation of the UIP puzzle. Christensen (2000) re-examines the modified UIP condition by applying McCallum's policy behaviour model. Ferreira (2004) extends McCallum's model by including other variables besides exchange rate changes, such as inflation and output gap movements in the policy reaction function. Mark and Moh (2007) examine the forward premium puzzle based on unanticipated central bank intervention in the foreign exchange market using continuous-time models. The analysis of the data and simulations of the theoretical model support the theory that the forward premium intensifies during periods of central bank intervention.

2.2. Transaction Costs

As mentioned in both the empirical and theoretical literature, transaction costs are an important explanation of the nonlinear dynamic adjustment in the exchange rate. The equilibrium models for exchange rate determination in the presence of transaction costs have been developed where deviations from PPP follow a mean-reverting nonlinear process in which the reversion speed has a direct relationship to the extent of the deviation from equilibrium. Although most studies to date have been applied to the PPP models, it could equally well be applied to UIP models.

Baldwin (1990) develops a model in which risk neutral homogenous agents have a choice of whether to invest in home or foreign currency denominated assets, with a small transaction cost of moving between these two assets. Under this model, he shows that the presence of small transaction costs will produce a band, within this band no trade will take place and the expected change in the exchange rate will not be affected by the interest rate differential. Only when the interest rate differential falls outside the band do exchange rate changes relate to the interest rate differential and UIP holds.

Otherwise, UIP does not hold due to less incentive for investors to change their investment behaviour.

Dumas (1992) analyses the nonlinear adjustment of deviations from PPP. He finds that within the transactions band the deviations from PPP are highly persistent but outside the band the dynamic process is fast and mean-reverting. He also mentions that the speed of adjustment depends on the size of the deviations. However, in the Dumas model, the deviations from PPP might persist for a long time, which is inconsistent with Michael et al. (1997). He also finds support for the asymmetric behaviour of the real exchange rate, which has a higher probability of moving away from parity than moving back to it.

Michael et al. (1997) analyse the equilibrium models of real exchange rate determination in the presence of transaction costs. Because of the transaction costs, the adjustment to PPP must be the same for positive and negative deviations from equilibrium, so they chose the ESTAR model. They find strong evidence that linearity is rejected and there is random walk behaviour for small deviations but fast adjustment for large deviations from PPP, which provides an alternative explanation for the failure of long-run PPP found in previous studies.

Chen and Wu (2000) re-examine PPP adjustment in Japan and Taiwan using the ESTAR model. The result of this study is similar to Michael et al. (1997). They state that there is no theoretical reason for distinguishing between the LSTAR and ESTAR models. The choice between the LSTAR and ESTAR models has to be based on the data. Granger and Teräsvirta (1994) suggest that the ESTAR model is useful when the data fluctuates rapidly over time. Samimi et al. (2009) use the LSTAR model based on annual and monthly data for the period 1975-2007. The results indicate that there is random walk behaviour for small deviations from PPP, but for larger deviations, adjustment is faster. In addition, transaction costs for annual and monthly series implies that the speed of transition between regimes is much faster for annual data than for monthly data.

2.3. Limits to Speculation

Motivated by the limited success of both statistical and economic based explanations, Lyons (2001) proposes a nonlinear model based on limits to speculation, which suggest that deviations from UIP occur and persist because no one is willing to trade on these deviations since other investment opportunities have a higher Sharpe ratio. Sarno et al. (2006) and Baillie and Kilic (2006) estimate exchange rates in a smooth transition regression (STR) framework and find strong evidence for the nonlinear relationship between spot rates and the forward premium. In the lower regime, UIP does not hold, but when Sharpe ratios are large, deviations from UIP become increasingly mean-reverting, relative to the size of the Sharpe ratios.

Sarno et al. (2006) have examined the limits to speculation hypothesis, using the relationship between spot rates and the forward premium in the context of an ESTR model. They find that the ESTR model is attractive because it allows a smooth transition between regimes and symmetric adjustment of the UIP deviations above and below the equilibrium level. They find strong evidence in support of nonlinearity in UIP deviations. In the lower regime, UIP fails to hold and UIP deviations are economically small and persistent. However, large deviations from UIP enable the exchange rate to move to the upper regime and UIP holds, so financial institutions could earn higher profits through a currency trading strategy and induce the exchange rate to mean-revert to the equilibrium.

Baillie and Kilic (2006) found a nonlinear asymmetric relationship between exchange rate changes and the lagged forward premium using the LSTR model. They estimated LSTR models with a variety of transition variables, such as the lagged forward premium, monetary and income fundamentals and also variables associated with time-varying risk premia. The transition variables, which include measures of income fundamentals are generally found to be ineffective transition variables. They use LSTR rather than ESTR because a logistic function is more general and flexible when describing exchange rate dynamics, whereas the exponential function required strong restrictions. They also included asymmetric dynamic behaviour within the model, and find the adjustment to UIP not only depends on the absolute size of the forward premium (Sarno et al., 2006), but also the sign of the magnitude of the forward premium. They found that UIP holds better when the US dollar is quoted at a premium and that UIP is significantly rejected when the US dollar is at a discount.

Amri (2008) examined the nonlinearities and asymmetries of exchange rates using the LSTR model with the risk adjusted forward premium as a transition variable. He finds the existence of nonlinear dynamics in the relationship between expected exchange rate movements and lagged forward premiums. This result confirms the evidence from other studies regarding the presence of the limits to speculation and transaction costs in the foreign exchange market. The results support the finding that the forward anomaly is apparent within the band, but UIP holds outside of it.

Baillie and Chang (2011) examined the forward premium anomaly based on the carry trade and momentum trading strategies. They use the LSTR model with transition variables related to the different currency trading strategies. UIP is found to hold in an upper regime where carry trades appear profitable, on the basis of interest rate differentials and where exchange rate volatility is high. The analysis of the carry trade is motivated by the limits to speculation hypothesise of Lyons (2001), where the existence of higher than usual profits from conducting carry trades attracts speculative capital and induces agents to trade these profitable opportunities away. Conversely, when carry trade profits appear low or negative, the forward bias is left unexploited and persists.

3. Data and Methodology

We have selected eight countries for the study and include a mix of developed and emerging economies to determine any differences between these two different types of country. The four developed economies used are the United Kingdom, Australia, Japan and Switzerland and their data runs from the beginning of 1986 to the end of 2009. These four countries were selected due to the importance of their foreign exchange markets and also their participation in the carry trade, especially for Japan. The four emerging countries used are Brazil, Mexico, Thailand and Russia, but due to a lack of data, will start from the early 1990's and run until the end of 2009, with Brazil beginning in 1994 m11, Mexico in 1994 m4, Thailand in 1995 m2 and Russia in 1995 m1. These four countries were selected due to Brazil and Russia being part of the important BRICS emerging economies, whilst both Thailand and Mexico have experienced currency crises over the recent past and it should be interesting to determine the effects of a crisis on UIP.

The data set consists of monthly data of the exchange rate and interest rate for both developed and emerging countries. The exchange rates are all bilateral against the US dollar, in terms of the domestic currency per dollar. Following other similar studies we have used the one month annualised interest rates for all countries. The data has been collected from two sources, Datastream and the Bank for International Settlements (BIS).

The exchange rate change is constructed as the first difference of the logarithm of monthly rates. The interest rate differential is the difference between the domestic interest rate and foreign interest rate. The Sharpe ratio is equal to ER_t/σ_{ER}, where ER_t is the currency excess return (or UIP deviation) and σ_{ER} is the standard deviation of the excess return. The exchange rate volatility is calculated by the appropriate univariate ARMA-GARCH (1,1) model for each currency, which could also be viewed as risk.

UIP suggests that the domestic currency is expected to depreciate when the domestic interest rate exceeds the foreign interest rate. The interest rate differential should equal the expected exchange rate change. The UIP condition is as follows:

$$E(s_{t+k}) - s_t = i_{t,k} - i^*_{t,k} \tag{1}$$

where s_t denote the logarithm of the exchange rate at time t, i_t and i_t^* are the domestic and foreign interest rate respectively. We follow the previous studies imposing rational expectations and risk neutrality, to produce the following empirical equation for UIP:

$$\Delta s_{t+k} = s_{t+k} - s_t = \alpha_1 + \beta_1 (i_{t,k} - i^*_{t,k}) + \varepsilon_{t+k} \tag{2}$$

The null hypothesis for UIP is that $\alpha_1=0$ and $\beta_1=1$. We also expect the error term to be stationary and uncorrelated with information available at time t. It is a widespread finding that the UIP slope coefficient is negative when using OLS estimation. This negatively correlated relationship between spot exchange rate returns and lagged interest rate differentials lead to the rejection of UIP, however this coefficient estimate might be regime-specific. We characterize nonlinear behaviour in the UIP regression as allowing for smooth rather than discrete adjustment using the smooth transition models.

3.1. Linearity Test

From the STR specification, the STR model can be reduced to a linear model when the speed of the transition is equal to zero. Therefore, it is necessary to test for the presence of linearity in the regression model by simply testing if γ is equal to zero in the transition function. Teräsvirta (1994) suggests using a second order and third order Taylor expansion to approximate the STR models. The auxiliary regression for testing for linearity is as follows:

$$\Delta s_t = \beta_0' x_t + \sum_{j=1}^{3} \beta_j' \tilde{x}' z_t^j + \varepsilon_t^* \tag{6}$$

where β'_0 and β'_j are coefficient matrices. The null hypothesis of linearity is H_o: $\beta_1=\beta_2=\beta_3=0$. The auxiliary regression in equation (6) could also be used to select the appropriate specification for the transition function. Teräsvirta (1994) also summarized the null and alternative hypotheses in testing for linearity as:

$$
\begin{array}{ll}
H_0: \beta_1 = \beta_2 = \beta_3 = 0 & H_1: nonlinear \\
H_0^1: \beta_3 = 0 & H_1^1: LSTR \\
H_0^2: \beta_2 = 0 | \beta_3 = 0 & H_1^2: ESTR \\
H_0^3: \beta_1 = 0 | \beta_2 = \beta_3 = 0 & H_1^3: LSTR
\end{array} \tag{7}
$$

First of all, if H_0 is rejected, a nonlinear regression is the most appropriate. Next the best nonlinear model is chosen dependant on H_0^1, H_0^2 and H_0^3. The problem is that before the linearity test, a linear autoregressive model using information criteria must be specified and the delay parameter should be determined by minimizing the p-value of the linearity test (Teräsvirta, 1994). The linearity tests are then assessed against the STR models with each of the potential transition variables.

3.2. Smooth Transition Regression (STR)

The STAR models have been widely used for nonlinear modelling and allow the regressive parameters to change slowly. The other nonlinear models, such as TAR models and Markov regime-switching models usually consider a sharp switch, which may not always be a reasonable assumption. The STAR models are more realistic, based on the economic theory that policies change gradually rather than sharply. Similar to the STAR models, in the STR models adjustment takes place in every period and the speed of adjustment is governed by the values of a transition variable. The difference between them is that the STR models include exogenous variables in the regression. The STR model[1] used to estimate UIP can be written as follows:

$$
\Delta s_{t+1} = [\alpha_1 + \beta_1 (i_t - i_t^*)] + [\alpha_2 + \beta_2 (i_t - i_t^*)] F(z_t, \gamma, c) + \varepsilon_{t+1} \tag{8}
$$

[1] Baillie and Kilic (2006) and Sarno et al. (2006) use the STR model to estimate UIP, but they use it with the forward premium. In this paper, we follow their approach, but replace the forward premium with the interest rate differential.

where F(.) is the transition function that determines the degree of reversion to UIP, z_t is the transition variable, γ is the transition parameter and c is a threshold parameter. There are two particularly useful forms of the STR models that allow for varying degrees of regressive decay, these are the LSTR and ESTR models.

3.2.1. Logistic Smooth Transition Regression (LSTR)

Since we use a logistic function to model the dynamics of adjustment, we can model asymmetric behaviour for both large and small transition variables and the exchange rate may behave differently with each. The logistic transition function is:

$$F(z_t, \gamma, c) = \frac{1}{1 + \exp(-\gamma(z_t - c)/\sigma_{z_t})} \tag{9}$$

The value of the logistic function is bounded between 0 and 1 and depends on the transition variable z_t as follows. If $z_t \to -\infty$, F(z_t, γ, c)$\to$0, F(z_t, γ, c)=0.5 for z_t=c, and F(z_t, γ, c)$\to$1 as $z_t \to +\infty$. The speed of reversion to UIP is determined by the transition variable and transition parameter. For a given value of a transition variable, the transition parameter γ determines the speed of transition between regimes, with low values of γ implying slower transition. The threshold parameter c can be interpreted as the threshold between the two regimes corresponding to F(z_t, γ, c)=0 and F(z_t, γ, c)=1. In the lower regime, the transition function F(z_t, γ, c)=0, (equation (8)) becomes a standard linear UIP regression:

$$\Delta s_{t+1} = [\alpha_1 + \beta_1(i_t - i_t^*)] + \varepsilon_{t+1} \tag{10}$$

While the upper regime with F(z_t, γ, c)=1, (equation (8)) becomes a different UIP regression:

$$\Delta s_{t+1} = [(\alpha_1 + \alpha_2) + (\beta_1 + \beta_2)(i_t - i_t^*)] + \varepsilon_{t+1} \tag{11}$$

The LSTR model nests the standard UIP regression, to which it would collapse in the absence of nonlinearity. Equation (8) could capture the dynamics between the exchange rate change and interest rate differentials as implied by the UIP theory. When the transition variable is less than a threshold parameter, the slope coefficient may take values far from unity (even negative values) and when the transition variable exceeds a threshold level this may induce investors to take positions, as such deviations from UIP become less persistent and the slope coefficient moves to the theoretical value of unity.

Granger and Teräsvirta (1993) and Teräsvirta (1994), suggest that the logistic function is much more reasonable, because it considers the asymmetric behaviour of the UIP deviations, which is more useful in this situation. Baillie and Kilic (2006) demonstrate this using the LSTR model, suggesting the logistic function can capture both the nonlinear dynamics and the asymmetric behaviour in the UIP relationship. The logistic function has become more popular in recent research because it is more general and more flexible in describing the exchange rate dynamics, whereas the exponential function imposes strong restrictions.

3.2.2. Exponential Smooth Transition Regression (ESTR)

Sarno et al. (2006) confirm the attractiveness of the ESTR model, because it allows a smooth transition between regimes and symmetric adjustment of the UIP deviations above and below the equilibrium level, which is consistent with the limits to speculation hypothesis. They also test for asymmetric nonlinearity considering the exchange rate changes with regard to positive and negative forward premia, but fail to reject the null hypothesis of no asymmetry in the STR model. The nonlinear modelling of the exchange rate literature concludes that the ESTR model is more realistic representation of the theory. The exponential function is:

$$G(z_t, \gamma, c) = 1 - \exp(-\gamma(\frac{z_t - c}{\sigma_{z_t}})^2) \tag{12}$$

The coefficients for the STR model are asymmetric around the threshold. If $z_t \rightarrow \pm\infty$, G($z_t$, γ, c)=1, G(z_t, γ, c)=0 for z_t=c. The lower and upper regimes are defined as the regimes corresponding to the two extreme values of the transition function, where G(z_t, γ, c)=0 and G(z_t, γ, c)=1. Investigation of the properties of the model in these two extreme regimes sheds light on the stability and dynamic properties of the STR model.

In this study, three different transition variables are used during the nonlinear estimation. Sharpe ratios, measured by the excess return in the UIP model divided by the standard deviation of excess return, follows the literature on limits to speculation and transaction costs. The interest rate differential is used as a transition variable based on the theory relating to central bank intervention and the carry trade strategy. The last transition variable is exchange rate volatility, which proxies the market risk in the context of UIP. Ichiue and Koyama (2011) have investigated whether failure of UIP is caused by exchange rate volatility, using a regime switching model. They find that low volatility tends to cause UIP failure as a higher Sharpe ratio attracts investors to the carry trade. Brunnermeier et al. (2009) find that the carry trade suffers losses when the volatility increases because the investors' risk appetite decreases and leads to the unwinding of the carry trade. Menkhoff et al. (2011) find returns from carry trade portfolios are lower in the periods of high foreign exchange market volatility. Also Baillie and Change (2011) find that UIP is more likely to hold during the high volatility regime.

4. Results and Discussion

Having satisfied the tests for stationarity, Table 1 reports the p-value from the tests for linearity suggested by Teräsvirta (1994). It shows evidence of nonlinear behaviour with UIP, when the transition variable is the interest rate differential, except for the UK and Australia. In this study, the best nonlinear model has been determined by the linearity test rather than choosing it in advance or running the regression separately for the positive and negative interest rate differentials. The hypothesis test results conclude that Mexico and Russia prefer the LSTR model. The linearity test results with the Sharpe ratio and exchange rate volatility as the transition variables are similar to the interest rate differential results, with some exceptions. Five out of eight countries produce evidence of nonlinear behaviour based on the Sharpe ratios, but only four for the exchange rate volatility.

Table 2 presents the estimation results of the OLS-UIP model. The conventional OLS regression results are consistent with previous studies in that the constant α_1 is very close to zero and often statistically insignificant, the β_1 coefficient is negatively signed in the developed countries but positive in the emerging countries. The negative β_1 coefficient is consistent with the literature in general and implies that the more the domestic interest rates exceed the foreign interest rates, the more the domestic currency tends to appreciate not depreciate, so as to offset the interest rate differential in favour of the home currency. The Wald test is a joint test where the null is the constant being equal to zero and slope coefficient equal to unity. We find only Japan and Brazil reject the null hypothesis which indicates UIP does not hold at the 5% level. To test for an unknown structural break point we run the Quandt-Andrews and Andrews-Ploberger breakpoint tests. The results conclude that there is no evidence of a break point in the OLS model[2].

The estimation results for both the unrestricted and restricted STR-UIP models using the Sharpe ratio as the transition variable are presented in Table 3. In the nonlinear STR models, the UK, Mexico and Thailand have the slope coefficients β_1 and β_2 correctly signed according to the limits to speculation hypothesis and transaction costs. We find a negative β_1 and positive β_2 such that the UIP holds exactly when the transition function equals one. This result implies that for small Sharpe ratios, UIP does not hold, but for increasingly large Sharpe ratios (which are likely to attract speculative capital), reversion to UIP can occur rapidly. It also implies that, since reversion to UIP can occur rapidly for large Sharpe ratios, most observations of the UIP deviations are in the lower regime, potentially generating substantial persistence, as predicted by the limits to speculation hypothesis. The other countries have a negative β_2 coefficient, which is inconsistent with the theory. The transition parameter γ explains the speed of the transition between regimes, the UK having a higher transition parameter, which demonstrates fast transition from one regime to the other, unfortunately it is insignificant. The threshold parameter c is nonzero and significant for all countries with the exception of Brazil and Thailand. The sum of $\beta_1+\beta_2$ measures the coefficients of the interest rate differentials in the upper regime, which are positive and close to one except for Brazil and Russia.

Several diagnostic statistics shown in Table 3 are used to compare the performance of the linear and nonlinear regression models. We prefer the regression model that has

[2] The results of the structural break tests are available from the authors on request.

higher values of the R^2 and log likelihood statistics. If the ratio of the nonlinear to the linear model residual standard deviation (r_l) is less than one, it means that the nonlinear model is better than the linear model as it has less residual standard deviation. We find that the UK and Mexico have a ratio for r_l which is less than one, indicating the nonlinear models are best, but Brazil, Thailand and Russia prefer the linear model. This result is not a surprise because these three emerging countries have a positive slope coefficient in the OLS-UIP model which already supports UIP. The p-value for the test of no remaining nonlinearity in the residuals is denoted by p_{RNL}, all the countries fail to reject the null hypothesis of no remaining nonlinearity. In the Wald test of the restrictions $\alpha_1+\alpha_2=0$ and $\beta_1+\beta_2=1$, we fail to reject the null hypothesis except for the UK and Mexico. These restrictions reflect the equilibrium (guaranteed global stability) condition that UIP holds, in other words the deviations from UIP are equal to zero.

In the nonlinear models, we also test the theoretical restriction that $\alpha_1=-\alpha_2$, $\beta_1=1-\beta_2$. The results for the restricted STR-UIP models in Table 3 have significantly large and positive β_2 coefficients and negative β_1 coefficients which indicate that the UIP condition is more likely to hold, as a higher value of the Sharpe ratio is associated with the transition function equal to unity. The estimated threshold parameter c is highly significant in all countries except for Brazil and Thailand. In addition when the Sharpe ratio is low, the transition function equals zero, so UIP does not hold. It is the same with the unrestricted model in that the threshold parameters are highly significant with some exceptions and the residuals have no remaining nonlinearity at the 5% level. The transition parameters for Brazil and Thailand are significantly larger than other countries, which implies a fast transition speed. The significant threshold parameters could be interpreted as indicating that for the foreign exchange traders to change their investment strategies and portfolios, the benefit from changing their position should be high enough to cover the costs of such a move. This interpretation is consistent with the transaction cost as well as limits to speculation theories.

Given the transition function we have estimated is bounded between zero and unity, it is useful to graph the transition functions over time and against the transition variables. In Figure 1, the plots give a clear idea of how the model represents UIP in the two different regimes. The lower regime is defined as the transition function being less than 0.5 and is characterized by very persistent deviations and is associated with low and economically unimportant Sharpe ratios. The estimated transition function in the UK is in the upper regime between 1992 (the ERM crisis) to 2002, combined with a positive β_2, which implies that UIP holds during the upper regime and is consistent with the literature demonstrating that UIP generally holds during the 1990s. In most cases regarding emerging countries, UIP is generally in the upper regime which suggests that speculative forces induce fast reversion to UIP. During the crises periods, the transition functions shift to the lower regime except for Thailand. Thailand before the Asian financial crisis had a relatively low transition function, however the value of the transition function during the Asian financial crisis period is close to one. The rapid changes of the transition functions caused by the frequently shifting Sharpe ratio generate substantial effects on the switch in UIP sustainability, such as in the UK and Thailand after the Asian crisis period.

Table 4 reports the average annualized Sharpe ratio for each currency in the first column, with the average Sharpe ratios running from 0.079 for the Thai baht to 0.6187 for the Brazilian real. Whereas the average Sharpe ratio reported by Lyons (2001) is 0.4 which is obtained from an equally weighted currency strategy on the six most liquid currencies. However in this paper, the results are generally lower than Lyons (2001) because different currencies are used and this is the case even for emerging markets currencies[3]. The second column in Table 4 describes the minimum value of the annualized Sharpe ratio which leads to a shift from the lower regime to the upper regime, producing a transition function equal to 0.5. The range of this minimum level is from 0.1948 to 1.1687, which is larger than the 0.4 found by Lyons (2001) except for the UK and Thailand. Therefore, it may not be sufficient to have a Sharpe ratio equal to 0.4 in order to induce the regime shifting and bias trading for the other three countries. The last column is the percentage of observations where the Sharpe ratio is less than or equal to the min SR, which is consistent with Sarno et al. (2006). The Sharpe ratio is too small to attract speculative capital, so traders would not exploit any bias.

The results from the estimation of the STR-UIP models with the interest rate differential as the transition variable are reported in Table 5. The β_2 coefficients are insignificant and negative in most cases when estimating the unrestricted model. Even in the restricted model, three out of six countries have positive coefficients but only Thailand is significant, which suggests that UIP does not hold in the upper regime. This result is not surprising, because for the developed countries (Japan and Switzerland), both are funding currencies for the carry trade due to their low interest rates. When the carry trade is profitable, the appreciation of the high interest rate currency encourages an increasing number of investors to follow the carry trade, adding to the appreciation. It also encourages the persistence of exchange rate changes, which led to deviations from UIP to grow larger and last longer. Due to the negative β_2 coefficients in emerging

[3] Also in this paper, the currency strategy includes only one currency. With the one-exchange-rate strategy it is hard to get a higher Sharpe ratio and requires a sophisticated multi-currency portfolio to diversify the risk.

countries, there is little evidence to support the nonlinear relationship in UIP when the interest rate differentials are used as the transition variable, with all the transition parameters being insignificantly different to zero. The sum of the coefficients $\beta_1+\beta_2$ are included in the table and combined with the Wald test results, indicate that the coefficient of the interest rate differential is close to one in Japan, Thailand and Russia. However, the β_1 coefficients for Brazil and Thailand in the lower regime are insignificant and larger than the value predicted by theory. The reason for this unexpected result can be found in the transition function. In Figure 2, the graph of the transition function against the transition variable for Brazil shows only a small number of observations (which are during the credit crisis) falling into the lower regime. But for Thailand, most of the observations are in the lower regime, especially after the Asian financial crisis. Along with the extremely large coefficients in the lower regime, the result suggests the estimated parameters for Thailand might not be realistic and may need to be estimated using alternative models.

Figure 2 shows the estimated transition function with the interest rate differential as the transition variable, plotted against both time and the transition variable. The transition function appears to be in the upper regime, close to unity during the first half of the 1990s in Japan but more volatile and switching between the lower and upper regimes for Switzerland. During this period, both Japan and Switzerland have relatively high interest rates, suggesting the dollar was the preferred funding currency for the carry trade. The interest rate differential is close to zero for another two periods, from mid-2001 to 2004 and after 2007, as US interest rates continued to decline following the internet bubble bursting and the September 11th attacks and after 2007 the US subprime crisis. The transition function against time in Japan shifts to the upper regime when the

Japanese yen is no longer attractive to investors as the funding currency for the carry trade. Along with the regression results, it supports the evidence that UIP holds in Japan during periods with lower US interest rates and implies that the strength of reversion to UIP depends on the interest rate differential. This result is consistent with Bansal and Dahlquist (2000) who find that UIP holds better when the US interest rates are lower. However, the transition function for Switzerland moves to the lower regime when the US dollar is the funding currency, suggesting UIP in Switzerland holds in those periods. However both the Japanese and Swiss results do not support UIP in most time periods other than during times of low US interest rates. Also the transition functions for emerging countries are more persistent in the upper and lower regimes.

The graphs of the transition functions against the transition variables show a clear pattern emerges for the exponential function and logistic function. Symmetric behaviour in the exponential function is found for Japan, Switzerland and Thailand. Based on the transition parameter, Japan has the lowest speed of transition and shifted more smoothly than the other two countries. An asymmetric function is found in the results for Brazil, Mexico and Russia. Compared to the exponential function, the logistic function in this case shifts more quickly and abruptly.

Table 6 presents the results for the STR-UIP models with the exchange rate volatility as the transition variable. The estimated unrestricted model's β_2 coefficients are positive and significant except for the Mexican peso, which implies that UIP tends to hold in the upper regime. The threshold parameter is highly significant but relatively small, which could explain the benefit to the foreign exchange traders of a change in their strategies, but might still not be enough of an incentive to change. The transition γ parameters are large but insignificant except for Australia, which demonstrates a fast transition speed and a more abrupt type of switching in these countries. The significant and fairly small γ parameter for Australia implies a gradual transition between regimes and the significant and positive β_2 coefficient is also found with the restricted model. Based on figure 3 it can be found that the transition function is close to unity during the crisis period when there is high exchange rate volatility. Combined with the results from the regression model, we find that UIP is more likely to hold in a regime where foreign exchange market volatility is high, which is consistent with the findings of Brunnermeier et al. (2009) and Baillie and Chang (2011). They find the carry trade loses money when there are increases in volatility. For the UK and Australia, the transition function stays at the upper regime for a longer time, but for Mexico and Thailand, there are only spikes in the upper regime, quickly moving back to the lower regime. The transition speed in the graphs when exchange rate volatility is the transition variable are faster than when the interest rate differential is used, as in Japan, Switzerland and Thailand.

5. Conclusions

This paper has considered the nonlinearity in the relationship between the exchange rate change and the interest rate differential. A number of STR models (ESTR and LSTR) with Sharpe ratios, interest rate differentials and exchange rate volatilities as transition variables have been analysed, having found evidence of non-linearity for the majority of countries tested. The estimation results based on the Sharpe ratio and the exchange rate volatility as transition variables generally give a better performance, which suggest that UIP holds in the upper regime, which is consistent with the transaction costs and limits to speculation hypothesis. However, the interest rate differential is generally found to be of less use as a transition variable and the nonlinear model did not support UIP overall.

With this transition variable, it appears it is the risk not the pure return that determines the transition. This suggests nonlinear adjustment and risk combined may be the best explanation of UIP deviations and suggests future research needs to concentrate on combining them within the model.

This study contributes to the UIP literature through a number of channels, there is clear evidence of non-linear adjustment of the exchange rate in UIP, which has been shown to occur when using the forward premium, but is also evident when using the UIP approach. In addition this has been shown to occur in both emerging as well as the usual developed economies. The results also provide a link between exchange rate risk and non-linear adjustment as we have shown that the transition variables which model risk are far more effective than those representing return, such as the interest rate differential.

The graphs of the transition function against the transition variables display the speed of the transition, suggesting variations across time depending on different types of exchange rate regimes and stability. Some graphs have an abrupt rather than the smooth transition, which is inconsistent with the theory based on central bank intervention and heterogeneous investors. So further analysis could centre on the TAR model or Markov switching type models.

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Table 1: Linearity Test

	Transition variable	H_0	H_0^1	H_0^2	H_0^3	*Model*
UK	Interest Rate Differential	0.4068	0.2402	0.1803	0.6125	Linear
	Sharpe Ratio	0.0944	0.6245	0.0165	0.5269	ESTR
	Exchange Rate Volatility	0.0392	1.0000	0.0045	0.5836	ESTR
Australia	Interest Rate Differential	0.3000	0.4766	0.1560	0.5533	Linear
	Sharpe Ratio	0.4658	0.3644	0.3702	0.3355	Linear
	Exchange Rate Volatility	0.0000	1.0000	0..0304	0.0000	ESTR
Japan	Interest Rate Differential	0.0034	0.9068	0.0002	0.2087	ESTR
	Sharpe Ratio	0.1360	0.6733	0.0427	0.2612	Linear
	Exchange Rate Volatility	0.9290	1.0000	0.6809	0.5933	Linear
Switzerland	Interest Rate Differential	0.0112	0.1297	0.0030	0.9037	ESTR
	Sharpe Ratio	0.3099	0.1438	0.4622	0.3421	Linear
	Exchange Rate Volatility	0.5739	1.0000	0.4275	0.2421	Linear
Brazil	Interest Rate Differential	0.0005	0.0186	0.0068	0.0576	ESTR
	Sharpe Ratio	0.0003	0.9235	0.0240	0.0001	ESTR
	Exchange Rate Volatility	0.3937	1.0000	0.1833	0.2656	Linear
Mexico	Interest Rate Differential	0.0000	0.0006	0.0000	0.0000	LSTR
	Sharpe Ratio	0.0579	0.8880	0.3982	0.0092	LSTR
	Exchange Rate Volatility	0.0000	0.0000	0.0010	0.0000	LSTR
Thailand	Interest Rate Differential	0.0331	0.8084	0.0636	0.0219	ESTR
	Sharpe Ratio	0.0017	0.6613	0.0013	0.0333	ESTR
	Exchange Rate Volatility	0.0119	0.6278	0.0278	0.0147	LSTR
Russia	Interest Rate Differential	0.0000	0.0059	0.0636	0.0003	LSTR
	Sharpe Ratio	0.0424	0.0849	0.0235	0.8065	ESTR
	Exchange Rate Volatility	0.5704	1.0000	0.9997	0.0301	Linear

Note: The table reports the p-value for Teräsvirta (1994) linearity test and the best model selected associated with various transition variables considered. The null and alternative hypotheses are demonstrated in equation (7). If the null hypothesis H_0 is rejected, a nonlinear regression is the appropriate one. The best nonlinear model is chosen dependent on H_0^1, H_0^2 and H_0^3, the smallest p-value. The last column gives the best model based on the linearity test.

Table 2: Estimation of OLS-UIP

	UK	AUS	JAP	SWI	BRA	MEX	THA	RUS
α_1	-0.0002	0.0012	-0.0070**	-0.0031	0.0031	0.0058	-0.0010	0.0023
β_1	-0.0295	-0.8156	-2.1875**	-1.3372	0.1571	0.1821	1.0768	0.5836***
Wald	1.3946	5.1147*	9.8570***	3.7904	12.073***	5.5142*	0.2349	5.5384*
R^2	0.0004	0.0034	0.0207	0.0072	0.0087	0.0146	0.0179	0.0616
LL	636.56	607.46	608.97	606.07	464.46	541.13	621.09	440.37

Note: The OLS result is run by the equation (2). The Wald test is a joint test of null hypothesis H_0: $\alpha_1=0$, $\beta_1=1$. LL is the log likelihood. ***, ** and * denote statistical significance at the 1%, 5% and 10% level.

Table 3: Estimation of STR-UIP (Sharpe Ratio)

	UK	BRA	MEX	THA	RUS
Unrestricted Model	ESTR	ESTR	LSTR	ESTR	ESTR
α_1	0.0034	-0.0100	0.1739^{***}	-0.0046	-0.0108
β_1	-6.2191^{**}	1.1509	-4.2806^{***}	0.3306	1.5150^{**}
α_2	-0.0037	0.0366^{*}	-0.1758^{***}	0.0087^{*}	0.0593^{*}
β_2	6.7666^{**}	-2.8299^{**}	4.7203^{***}	1.1404	-2.3012^{***}
c	0.3038^{***}	0.1581	-1.5384^{***}	0.1156	0.2321^{***}
γ	20.107	1.3939	2.7052^{***}	8.7522	3.0950
$\beta_1+\beta_2$	0.5475	-1.6790	0.4379	1.4710	-0.7862
R^2	0.0156	0.0180	0.1922	0.0414	0.0864
LL	636.489	258.221	374.683	411.674	221.576
Wald test	3.6666^{***}	1.4228	3.0720^{**}	1.7024	2.2372
r_1	0.9919	1.1874	0.9885	1.1384	1.2388
p_{RNL}	0.3819	0.3874	0.5639	0.1172	0.6688
BIC	-463.66	-84.96	-253.25	-278.44	-18.35
Q(4)	31.07^{***}	7.77	1.63	9.10^{**}	9.47^{**}
Q(8)	40.25^{***}	9.71	6.06	24.96^{**}	10.56
Restricted Model	ESTR	ESTR	LSTR	ESTR	ESTR
α_2	0.0059	-0.0047	-0.1722^{***}	0.0038	-0.0354
β_2	3.3892^{**}	2.8704	5.3286^{***}	0.7410	2.7690
c	2.2632^{**}	0.0268	-1.4973^{***}	0.1261	1.7596^{***}
γ	0.3257	66.922	3.5423^{***}	12.408	1.7444
R^2	0.0548	0.0178	0.1538	0.0305	0.0855
LL	642.14	255.12	370.22	410.50	221.50
p_{RNL}	0.0666	0.9792	0.3224	0.2734	0.5165
BIC	-486.23	-89.06	-254.85	-286.76	-28.48
Q(4)	15.82^{***}	10.09^{**}	4.1978	9.7823^{**}	9.3582^{*}
Q(8)	22.27^{***}	12.07	10.99	26.86^{***}	10.72

Note: The unrestricted STR-UIP model is estimated by equation (8). LL is the log likelihood. The Wald test is for the null hypothesis $\alpha_1+\alpha_2=0, \beta_1+\beta_2=1$. p_{RNL} denotes the p-value for the test of no remaining nonlinearity in the residuals. r_1 is the ratio of nonlinear to linear model residual standard deviations. The Q(4) and Q(8) are the tests for the serial correlation in the residuals up to lags 4 and lags 8. The restriction is $\alpha_1=-\alpha_2, \beta_1=1-\beta_2$. ***, ** and * denote statistical significance at the 1%, 5% and 10% level.

Table 4: Sharpe Ratios

	SR Mean	min SR	%Obs SR≤min SR
UK	0.2989	0.3383	60%
BRA	0.6187	0.6554	74%
MEX	0.1722	1.1687	97%
THA	0.0790	0.1948	66%
RUS	0.2553	0.4561	84%

Note: the first column of the table is the mean of Sharpe ratio (SR), which is calculated by the realized excess returns divided by the standard deviation of excess returns on an annual basis. The second column (min SR) is the minimum value of the annualized Sharpe ratio which leads to a shift from the lower regime to the upper regime, defined here is the value of the transition function equal to 0.5. The last column is the percentage of observations where the annualized Sharpe ratio is less than or equal to the minimum Sharpe ratio.

Table 5: Estimation of STR-UIP (Interest Rate Differential)

	JAP	SWI	BRA	MEX	THA	RUS
Unrestricted Model	ESTR	ESTR	LSTR	LSTR	ESTR	LSTR
α_1	-0.0086***	0.0324	-0.1691	0.0033	-0.0063	-0.0019***
β_1	-1.4103	-6.2844	26.150	0.4897**	18.700	0.6674***
α_2	0.1793	-0.0493	0.1730	0.3117***	0.0076	0.0933***
β_2	1.6254	-0.0111	-26.041	-7.6541***	-17.876	-1.1689***
c	-0.0016***	0.0228	0.0062***	0.0334***	0.0003	0.0335***
γ	0.0167	1.1031	31.544	194.85	28.675	546.2***
$\beta_1+\beta_2$	0.2151	-6.2955	0.1090	-7.1644	0.8240	0.8568
LL	599.945	616.604	259.927	363.463	412.321	223.386
Wald test	3.4867**	23.843***	8.715**	14.501***	3.1875	1.7019
p_{RNL}	0.2310	0.3928	0.8010	0.0079	0.0767	0.2899
BIC	-405.79	-420.08	-85.02	-227.36	-276.21	-18.63
Restricted Model	ESTR	ESTR	LSTR	LSTR	ESTR	LSTR
α_2	0.0207	0.0157**	1.0768	-0.0096	0.0019	0.0141**
β_2	6.9989	-12.086***	-161.62	2.8799	3.6784**	-2.0251***
c	-0.0062	0.0012***	0.0067***	0.0054***	0.0006	0.0386***
γ	0.1068	1.1743**	287.75	1034.5	0.6157*	409.3
LL	599.934	607.615	255.780	353.282	413.721	221.312
p_{RNL}	0.2286	0.5510	0.9125	0.0545	0.0698	0.0070
BIC	-416.99	-413.36	-87.04	-217.52	-289.68	-24.78

Note: It is the same as the Table 3.

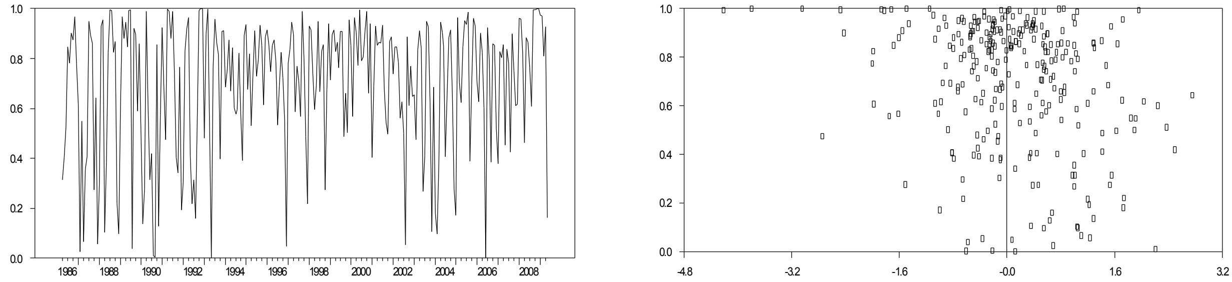
Table 6: Estimation of STR-UIP (Exchange Rate Volatility)

	UK	AUS	MEX	THA
Unrestricted Model	ESTR	ESTR	LSTR	LSTR
α_1	-0.0145	0.0058***	0.0033	-0.0002***
β_1	-6.8761*	-1.8658***	0.4708*	-0.3963***
α_2	0.0157	-0.2267***	0.0744***	0.0032***
β_2	6.6502*	7.287***	-2.3515***	2.0741***
c	0.0003***	0.0005***	0.0075***	0.0013***
γ	220.39	0.0991***	533.55	3485.2
$\beta_1+\beta_2$	1.4367	5.2629	-1.8807	1.6778
LL	633.248	601.477	354.735	411.892
Wald test	7.3376**	9.0692***	5.1629**	6.3287***
p_{RNL}	0.2196	0.2702	0.0506	0.0641
BIC	-464.80	-427.80	-216.81	-278.88
Restricted Model	ESTR	ESTR	LSTR	LSTR
α_2	-0.0122	-0.0014	-0.0073**	0.0002***
β_2	7.7285***	3.6560***	1.0619***	1.3963***
c	0.0007***	0.0005***	0.0511	0.0013***
γ	20.427*	16.265	24.130	4558.9
LL	634.076	595.438	354.588	410.726
p_{RNL}	0.3183	0.3447	0.0495	0.1202
BIC	-477.69	-426.91	-277.02	-287.20

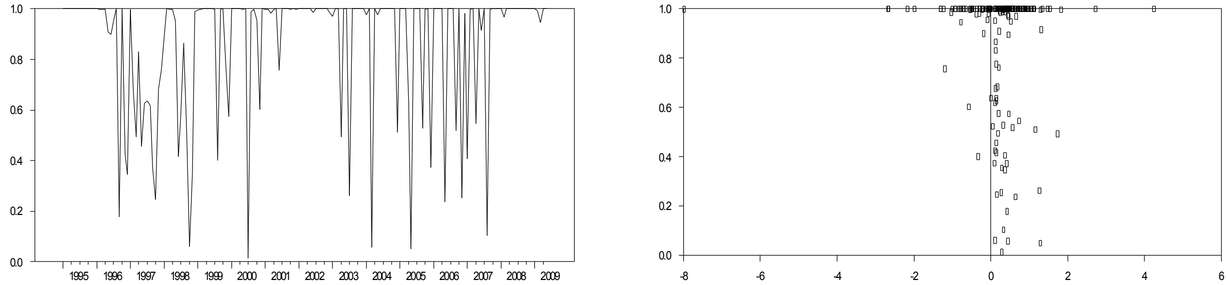
Note: It is the same as the Table 3.

Figure 1: Transition Function (Sharpe Ratio)

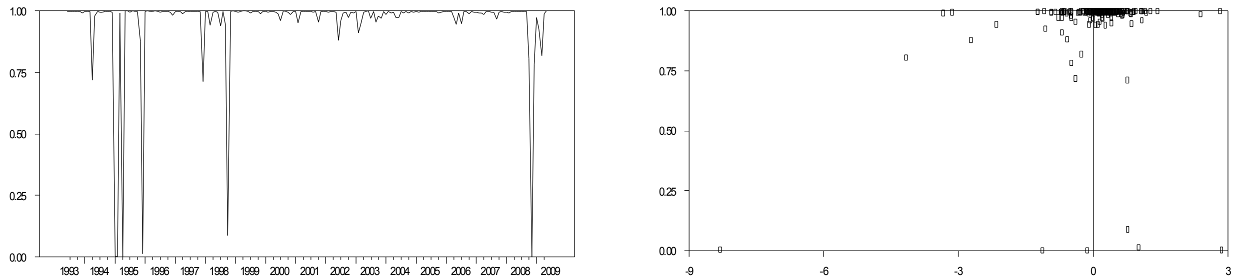
UK



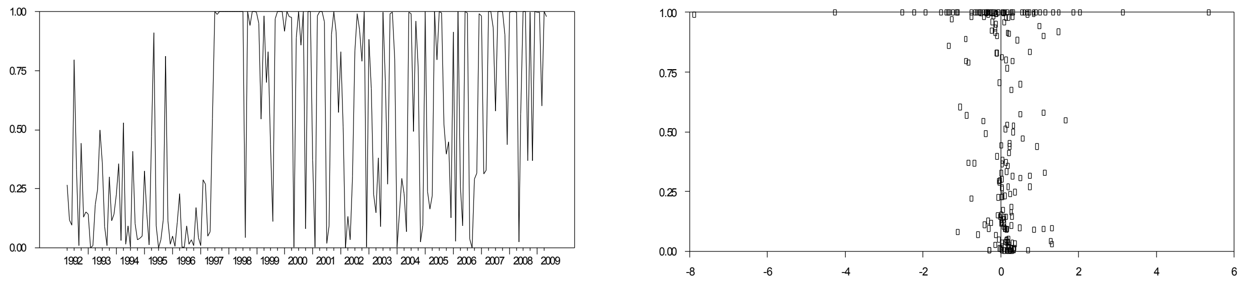
Brazil



Mexico



Thailand



Russia

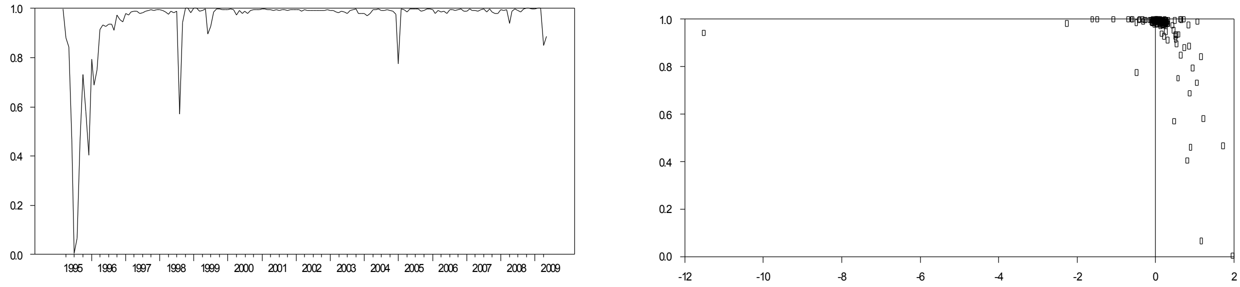
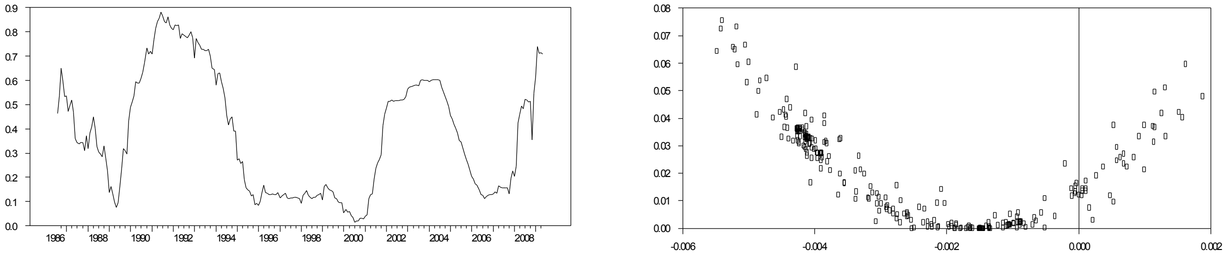
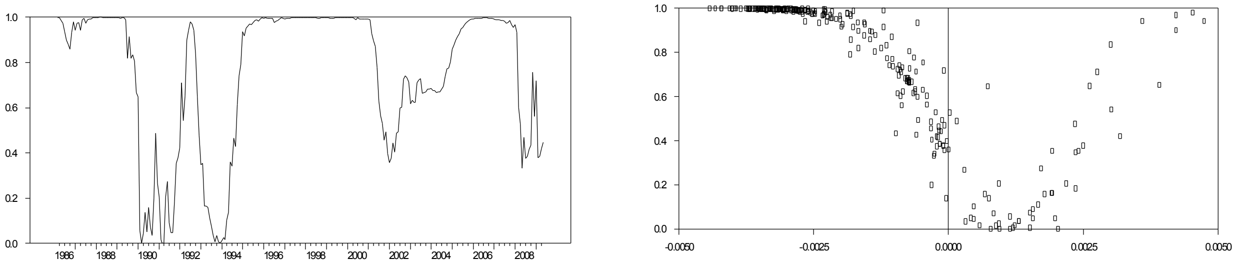


Figure 2: Transition Function (Interest Rate Differential)

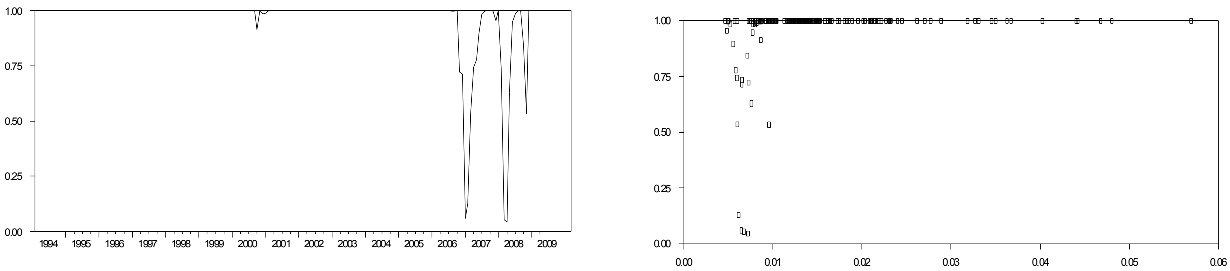
Japan



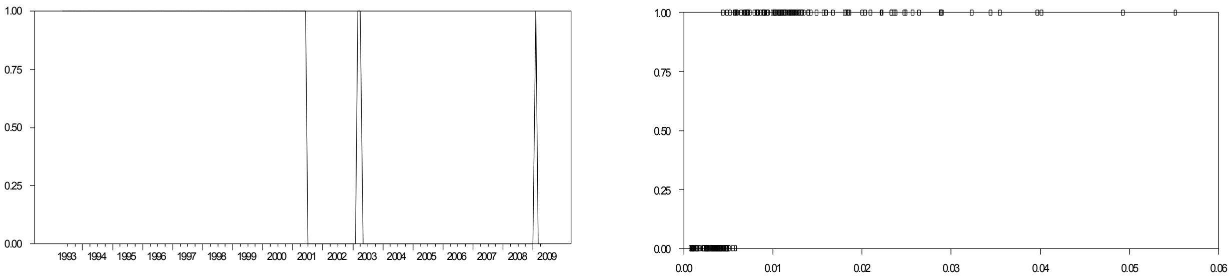
Switzerland



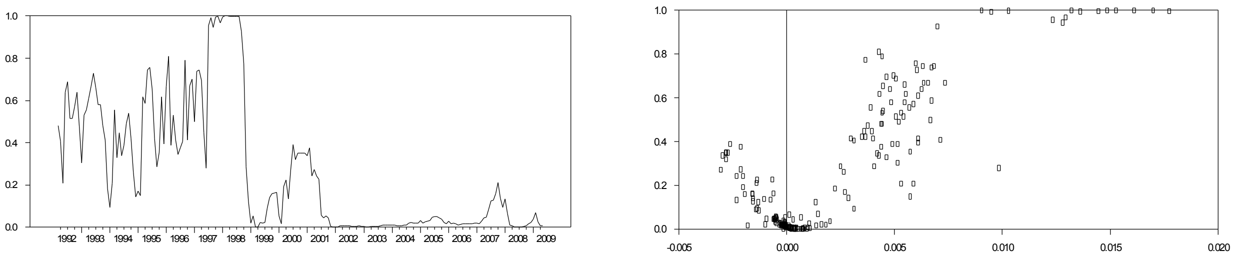
Brazil



Mexico



Thailand



Russia

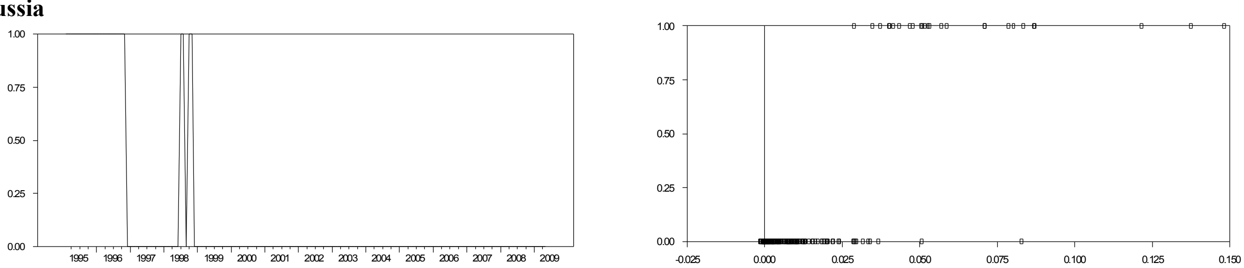
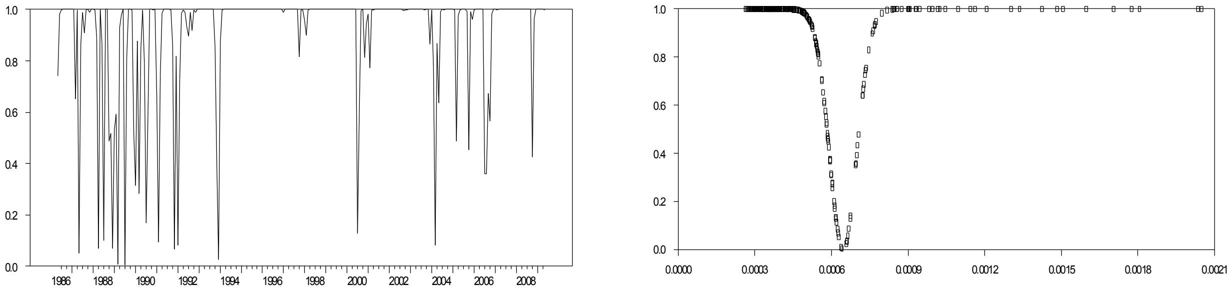
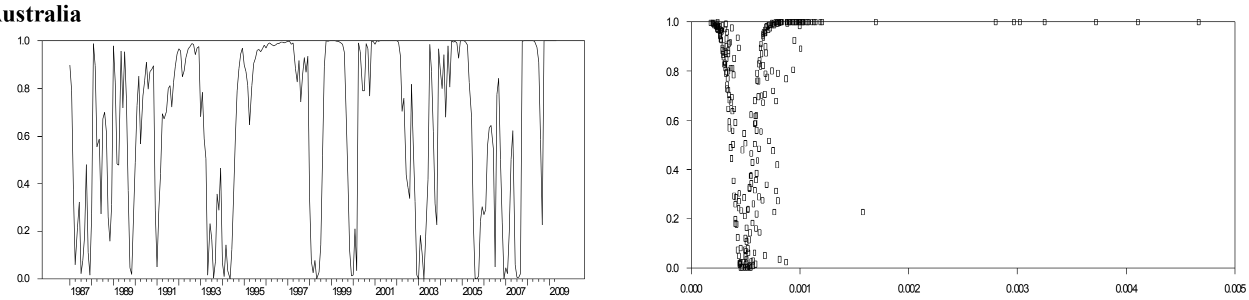


Figure 3: Transition Function (Exchange Rates Volatilities)

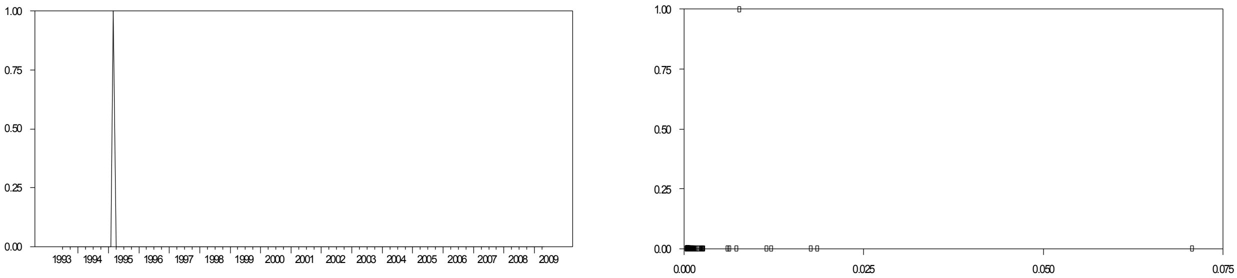
UK



Australia



Mexico



Thailand